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SIMPLIFIED COMPOSITE MICROMECHANICS EQUATIONS FOR STRENGTH,  
FRACTURE TOUGHNESS, IMPACT RESISTANCE AND ENVIRONMENTAL  
EFFECTS

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# Simplified Composite Micromechanics Equations for Strength, Fracture Toughness, Impact Resistance and Environmental Effects

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SIMPLIFIED COMPOSITE MICROMECHANICS EQUATIONS FOR STRENGTH,  
FRACTURE TOUGHNESS, IMPACT RESISTANCE AND ENVIRONMENTAL EFFECTS

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SUMMARY

A unified set of composite micromechanics equations of simple form is summarized and described. This unified set includes composite micromechanics equations for predicting (1) ply in-plane uniaxial strengths; (2) through-the-thickness strength (interlaminar and flexural); (3) in-plane fracture toughness; (4) in-plane impact resistance; and (5) through-the-thickness (interlaminar and flexural) impact resistance. Equations are also included for predicting the hygrothermal effects on strength, fracture toughness and impact resistance. Several numerical examples are worked out to illustrate the ease of use of the various composite micromechanics equations. The numerical examples were selected, in part, to demonstrate the interrelationships of the various constituent properties in composite strength and strength-related behavior, to make comparisons with available experimental data and to provide insight into composite strength behavior.

INTRODUCTION

The several strengths (stresses at fracture) of unidirectional composites are fundamental to analysis/design of fiber composite structures. Some of these strengths are determined by physical experiments. Others are not easily amenable to direct measurement by testing. In addition, testing is usually time consuming, costly, and the composite must have been made prior to testing. Furthermore, parametric studies of the effects of fiber volume ratio on properties such as impact resistance and fracture toughness can only be made by an extensive combination of tests. Another approach is the use of composite micromechanics to derive equations for predicting composite strengths based on constituent (fiber and matrix) properties. Over the last twenty years, composite micromechanics has been used to derive equations for predicting selected composite strengths (ref. 1). However, these equations are not readily available since equations for different strengths are scattered throughout the literature.

Herein, a unified set of composite micromechanics equations is summarized and described. The set includes simple equations for predicting ply (unidirectional composite) strengths using constituent properties. Equations are for: (1) tensile strengths (in-plane and through-the-thickness), (2) flexural strength, (3) impact resistance, and (4) fracture toughness. Also, equations are presented for the effects of (1) moisture, and (2) temperature. Results predicted by these equations are compared with available experimental data.

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These data are primarily from Refs. 1 to 5. The equations are summarized in subsets corresponding to related strengths such as in-plane, through-the-thickness, etc. The description consists of the significance of the participating variables in the equations of each subset, several numerical examples and possible implications.

The equations of each subset (strengths, fracture toughness, impact resistance and hygrothermal degradation effects) are summarized in chart form (labeled figures). This allows the equations for each subset to be in one page for convenience of use and identification of interrelationships. Constituent material properties used in the numerical examples are tabulated and identified with the same symbol used in the equations. The numerical examples are presented in narrative form, rather than tabular, in order to conserve space. The symbols used are summarized in the Appendix for convenience of reference.

Many of the equations included in this composite micromechanics unified set appear in their present simplified form for the first time. These equations evolved from continuing research on composite micromechanics and composite computational mechanics at Lewis Research Center. Also, this is the first unified set which provides a quantified description of composite strength and strength-related behavior (fracture toughness and impact resistance) at the micromechanistic level.

#### SYMBOLS

|               |                                    |
|---------------|------------------------------------|
| c             | heat capacity                      |
| D             | diffusivity                        |
| d             | diameter                           |
| E             | modulus of elasticity              |
| G             | shear modulus                      |
|               | impact energy density              |
| K             | heat conductivity                  |
| k             | volume ratio                       |
| M             | moisture - percent by weight       |
| $N_f$         | number of filaments per roving end |
| P             | property                           |
| RHR           | relative humidity ratio            |
| S             | strength                           |
| $\mathcal{L}$ | fracture "toughness"               |
| T             | temperature                        |
| t             | thickness                          |
| x,y,z         | structural reference axes          |
| 1,2,3         | ply material axes                  |
| $\alpha$      | thermal expansion coefficient      |
| $\beta$       | moisture expansion coefficient     |

|            |                              |
|------------|------------------------------|
| $\delta$   | interfiber, interply spacing |
| $\epsilon$ | fracture strain, strain      |
| $\theta$   | ply orientation angle        |
| $\lambda$  | weight percent               |
| $\rho$     | density                      |
| $\sigma$   | stress                       |

Subscripts:

|          |  |
|----------|--|
| F        | fiber property                                     |
| C        | compression property                               |
| D        | dry property                                       |
| G        | glass-transition                                   |
| F        | flexural   |
| L        | ply property                                       |
| M        | matrix property                                    |
| S        | shear  |
| SB       | short beam shear                                   |
| T        | tension  |
| V        | void   |
| W        | wet  |
| O        | reference property, temperature                    |
| $\infty$ | saturation   |
| 1,2,3    | direction corresponding to 1,2,3 ply material axes |

## COMPOSITE MECHANICS -- DEFINITIONS AND CONSTITUENT MATERIALS

The branch of composite mechanics which provides the formal structure to relate ply uniaxial strengths to constituent properties is called composite micromechanics. Composite micromechanics for uniaxial strengths is identified concisely in the schematic in figure 1. The schematic in this figure defines the inputs to composite micromechanics and the outputs. The inputs consist of constituent material (fiber/matrix) properties, geometric configuration, environmental conditions, and the fabrication process. The outputs consist of ply uniaxial strengths, impact resistance, fracture toughness and hygrothermal effects.

The formal structure of composite micromechanics (concepts, math-models and equations) is developed based on certain assumptions (consistent with the physical situation) and the principles of solid mechanics. The four main assumptions made in deriving the equations described herein are: (1) the ply resists loads as depicted schematically in figure 2; (2) the ply and its constituents behave linearly elastic to fracture as is illustrated in figure 3; (3) the ply uniaxial strengths are associated with their respective fracture modes shown in figure 4; and (4) there is complete bond at the interface of the constituents. Though the principles of solid mechanics can be used with

various levels of mathematical sophistication, the mechanics of materials was used in deriving the equations summarized herein because it leads to explicit equations of simple form for each property.

Properties along the fiber direction (1-axis, fig. 2) are conventionally called longitudinal; those transverse to the fiber direction (2-axis, fig. 2) are called transverse; the in-plane shear is also called intralaminar shear (1-2 plane, fig. 2). Those through the thickness (3-axis, fig. 2) are called interlaminar properties. All ply properties are defined with respect to the ply material axes denoted by 1, 2 and 3 in figure 2 for description/analysis purposes. Most ply properties are denoted by a letter with suitable subscripts. The subscripts are selected to identify type of property (ply, fiber, matrix), plane, direction, and sense in the case of strengths. For example,  $S_{L11T}$  denotes ply longitudinal tensile strength while  $S_{FT}$  denotes fiber tensile strength. Though this notation may seem cumbersome, it is necessary to properly differentiate among the multitude of ply and constituent properties.

A variety of fibers have been used to make composites. Some of these are summarized in table 1 with their respective properties needed for composite micromechanics. Similarly, some typical matrix resins are summarized in table 2.

#### UNIAXIAL STRENGTHS -- IN-PLANE

There are five in-plane ply uniaxial strengths. These are identified as: (1) longitudinal tension ( $S_{L11T}$ ); (2) longitudinal compression ( $S_{L11C}$ ); (3) transverse tension ( $S_{L22T}$ ); (4) transverse compression ( $S_{L22C}$ ); and (5) in-plane or intralaminar shear ( $S_{L12S}$ ). The fracture modes associated with each uniaxial strength are depicted schematically in figure 4. Note that there are three different and distinct fracture modes for longitudinal compression (fig. 4-b): (1) fiber compression (shear plane) fracture; (2) delamination transverse splitting or panel buckling; and (3) fiber microbuckling.

The composite micromechanics equations for the ply uniaxial strengths are summarized in figure 5 with attendant schematics. The schematics define the load direction, fiber orientation and the notation used in the micromechanics equations. The first five equations describe the in-plane uniaxial strengths, respectively:  $S_{L11T}$ ,  $S_{L11C}$ ,  $S_{L22T}$ ,  $S_{L22C}$ , and  $S_{L12S}$ . The last equation is for the void effect on the resin strength ( $S_m$ ) and also provides lower bound estimates on  $S_{L22T}$ ,  $S_{L22C}$  and  $S_{L12S}$  as will be described later.

The following are observed from the micromechanics equations for ply uniaxial strengths: (1)  $S_{L11T}$  depends on  $S_{FT}$  and the fiber compression fracture mode for  $S_{L11C}$  depends on  $S_{FC}$ . These are the only two that are fiber strength dominated. (2) The delamination/splitting for  $S_{L11C}$  depends on matrix shear strength (through  $S_{L12S}$  (eq. 5)) and the matrix tensile strength and, therefore, is resin strength dominated. (3) The microbuckling fracture mode for  $S_{L11C}$  depends strongly on the shear modulus and mildly on the modular ratio ( $G_m/G_{f12}$ ) and, therefore, is resin stiffness dominated. (4) The other three ( $S_{L22T}$ ,  $S_{L22C}$  and  $S_{L12S}$ ) depend strongly on the respective resin strengths and are, therefore, resin strength dominated. (5) The fiber volume ratio affects strongly  $S_{L11T}$  and  $S_{L11C}$  (fiber compressing or fiber microbuckling) which are the fiber strength or shear stiffness dominated ply strengths). (6) The fiber volume ratio affects mildly  $S_{L22T}$ ,  $S_{L22T}$ ,  $S_{L22C}$ ,  $S_{L12S}$  and  $S_{L11C}$  (delamination/



shear) which are the resin-strength dominated ply uniaxial strengths. (7) The voids influence the matrix strength. Several examples below illustrate use of the uniaxial strength equations in figure 5.

Example 3.1. Calculate the ply tensile strength ( $S_{L11T}$ ) of a graphite fiber (AS)/intermediate modulus, high strength (IMHS) epoxy (AS/E) composite with 0.6 fiber volume ratio. From table 1,  $S_{ft} = 350$  ksi and from equation (1) (fig. 5),  $S_{L11T} = 210$  ksi which is the same as the measured value in table 3.

Example 3.2. Calculate the ply compression strength for an AS/E (IMHS) composite with 0.6 fiber volume ratio. All three equations (eq. (2), fig. 5) should be used. To use the first equation,  $S_{fc}$  must be known. If it is not known,  $S_{fc} \approx 0.9 S_{ft}$  is a good approximation for graphite fiber/matrix composites (ref. 6). Using this approximation and respective values for tables 1 and 2 in equation (2) figure 5 from the first equation:

$$S_{L11C} = 0.6 \times 0.9 \times 350 = 189 \text{ ksi}$$

from the second equation (note need evaluate  $S_{L12S}$  from eq. (5), example 3.5 with incomplete bond)

$$S_{L11C} = 10.0 \times 8.1 + 2.5 \times 15 = 118 \text{ ksi}$$

from the third equation,

$$S_{L11C} = 0.185 / [1.0 - 0.6 (1.0 - 0.185 / 2.0)] = 406 \text{ ksi}$$

A conservative approach is to select the lowest value or  $S_{L11C} = 118$  ksi. This is about 69 percent of the typical measured value of 170 ksi in table 3. The value of 189 ksi predicted by the first equation is also reasonable. This value could be used in laminates which have other than  $0^\circ$  plies on the outside.

Example 3.3. Calculate the ply transverse tensile strength ( $S_{L22T}$ ) for an AS/E (IMHS) composite with 0.6 fiber volume ratio. From equation (3) and respective values from tables 1 and 2

$$S_{L22T} = [1.0 - (\sqrt{0.6} - 0.6) \times (1.0 - 0.5/2.0)] \times 15 = 13 \text{ ksi}$$

This is about twice the measured value of 7 ksi in table 3. One major reason for this difference is the complete bond at the fiber/matrix interface assumed in deriving equation (3), figure 5. Incomplete bond at the interface may be approximated by assuming the presence of voids. Assuming about 5 percent voids by volume ( $k_v = 0.05$ ) and using equation (6) (fig. 5), the reduced or degraded resin tensile strength

$$S_{mT} = \{1.0 - [4 (0.05) / (1.0 - 0.6) \pi]^{1/2}\} \times 15 = 9.0 \text{ ksi}$$

Using this reduced resin strength in equation (3) (fig. 5)  $S_{L22T} = 7.8$  ksi which is a reasonable estimation compared to the measured value of 7 ksi.

The above calculations lead to the conclusion that estimation of  $S_{L22T}$ , then, requires two steps:

1. Degradation of  $S_{mT}$  due to 5 percent voids by volume ( $k_v = 0.05$ ) as predicted by equation 6 (fig. 5).
2. Substitution of the degraded  $S_{mT}$  in equation (3).

Though the value of 5 percent voids may seem somewhat arbitrary, it is reasonable since equation (3), figure 5, does not account for factors such as



nonuniform fiber distribution within the ply, incomplete (partial) bond at the fiber/matrix interface, and possible differences in the in situ resin matrix properties compared to the neat resin properties.

Example 3.4. Calculate the transverse compression strength ( $S_{\perp 22C}$ ) for an AS/E (IMHS) with 0.6 fiber volume ratio. From equation (4) and respective values from tables 1 and 2

$$S_{\perp 22C} = [1.0 - (\sqrt{0.6} - 0.6) (1.0 - 0.5/2.0)] \times 35.0 = 30.4 \text{ ksi}$$

This value is about 85 percent of the typical value in table 3. It is worth noting that the interfacial bond and fiber nonuniformity are not critical in transverse compression and, therefore, do not contribute to resin compression strength degradation.

Example 3.5. Calculate the intralaminar shear strength ( $S_{\perp 12S}$ ) for an AS/E (IMHS) with 0.6 fiber volume ratio. From equation (5) and respective values from tables 1 and 2

$$S_{\perp 12S} = [1.0 - (\sqrt{0.6} - 0.6) (1.0 - 0.185/2.0)] \times 13 = 10.9 \text{ ksi}$$

This value is about 21 percent greater than the typical measured value 9 ksi, table 3. This value is reasonable in view of the nonuniform fiber distribution bonding condition at the interface and deviations in in situ properties from neat resin properties as was mentioned for  $S_{\perp 22T}$  (example 3.2). A closer estimate to the measured value may be obtained by degrading the matrix shear strength  $S_{mS}$  assuming 2 percent voids ( $k_v = 0.02$ ) in equation (6), figure 5. The result is  $S_{\perp 12S} = 8.1$ . It is worth noting that the various factors that affect the transverse tensile strength also affect the intralaminar shear strength but not as severely.

Example 3.6. Calculate the effect of voids on the ply transverse tensile strength of an AS/E (IMHS) with 0.6 fiber volume ratio ( $k_f = 0.6$ ) and 0.02 void volume ratio ( $k_v = 0.02$ ). This is accomplished using the following three steps:

1. Voids effect on  $S_{mT}$  (eq. (6), fig. 5).  
 $S_{mT} = \{1.0 - [4(0.02)/(1.0 - 0.6)\pi]^{1/2}\} \times 15 = 11.2 \text{ ksi}$
2. Incomplete interfacial bond effects  
 $S_{mT} = \{1.0 - [4(0.05)/(1.0 - 0.6)\pi]^{1/2}\} \times 11.2 = 6.8 \text{ ksi}$
3. Transverse tensile strength (eq. (3), fig. 5)  
 $S_{\perp 22T} = [1.0 - (\sqrt{0.6} - 0.6) (1 - 0.5/2.0)] 6.8 = 5.9 \text{ ksi}$

Note that the two void ratios ( $k_v = 0.02$  and  $k_v = 0.05$ ) are not additive since equation (6) is nonlinear.

Example 3.7. Calculate the lower bound of the ply transverse tensile strength for an AS/E (IMHS) composite with  $k_f = 0.6$ . For this case, we use equation (6), figure 5, with:  $k_v = 0.6$ ,  $k_f = 0.0$  and  $S_{\perp 22T} = S_m$ .  
 $S_{\perp 22T} = \{1.0 - [4(0.6)/\pi]^{1/2}\} \times 15 = 1.9 \text{ ksi}$

This value is about 27 percent of the typical measured value of 7 ksi and about 15 percent of that predicted by equation (3), figure 5, without any degradation. The lower bound is overly pessimistic for acceptable composites and should be used only by in composites with no interfacial bond. Lower bound

estimates on ply transverse compression ( $S_{22C}$ ) and ply intralaminar shear strength ( $S_{12S}$ ) are obtained by following the same procedure.

#### UNIAXIAL STRENGTHS -- THROUGH-THE-THICKNESS

There are six through-the-thickness uniaxial strengths. These are identified as: (1) longitudinal interlaminar shear (parallel to the fiber direction), ( $S_{13S}$ ); (2) transverse interlaminar shear (transverse to the fiber direction), ( $S_{23S}$ ); (3) longitudinal short-beam-shear (parallel to the fiber direction), ( $S_{13SB}$ ); (4) transverse short-beam-shear (transverse to the fiber direction), ( $S_{23SB}$ ); (5) longitudinal flexural (bending) ( $S_{11F}$ ); and (6) transverse flexural ( $S_{22F}$ ). The composite micromechanics equations for these uniaxial strengths are summarized in figure 6 with attendant schematics. The first six equations describe the six through-the-thickness uniaxial strengths, respectively:  $S_{13S}$ ,  $S_{23S}$ ,  $S_{13SB}$ ,  $S_{23SB}$ ,  $S_{11F}$  and  $S_{22F}$ . The last equation describes the void effects on the resin strength and can also be used as a lower bound on ply strengths dominated by the resin as was mentioned previously.

The following are observed from the composite micromechanics equations in figure 6: (1)  $S_{12S}$  is the same as  $S_{12S}$ ; (2)  $S_{23S}$  depends strongly on the resin shear strength ( $S_{mS}$ ) and mildly on  $k_f$  and  $G_m/G_{f23}$ ; (3) the short-beam-shear strengths  $S_{13SB}$  and  $S_{23SB}$  are 1.5 times their respective interlaminar shear strengths ( $S_{13S}$  and  $S_{23S}$ ); (4) the longitudinal flexural strength ( $S_{11F}$ ) is fiber dominated and, thus, depends strongly on  $k_f$ ,  $s_{fT}$  and  $S_{fC}$ ; (5) the transverse flexural strength ( $S_{22F}$ ) is matrix strength dominated and, thus, depends strongly on  $S_{mT}$  and  $S_{mC}$  but it depends mildly on  $k_f$  and  $E_m/E_{f22}$ ; (6) the voids degrade matrix strength depending nonlinearly on both  $k_v$  and  $k_f$ . Several examples below illustrate use of the equations in figure 6.

Example 4.1. Calculate the longitudinal interlaminar shear strength ( $S_{13S}$ ), for an AS/E (IMHS) composite with 0.6 fiber volume ratio. This is the same as  $S_{12S}$ . However, we go through the steps again for completeness. Using equation (4), the first of equation (1), figure 6, and respective property values from tables 1 and 2:

1. Incomplete bond simulation ( $k_v = 0.02$ )  
 $S_{mS} = \{1.0 - [4(0.02)/(1.0 - 0.6)\pi]^{1/2}\} \times 13 = 9.7 \text{ ksi}$
2. Longitudinal interlaminar shear strength  
 $S_{13S} = [1.0 - (\sqrt{0.6} - 0.6)(1 - 0.185/2.0)] \times 9.7 = 8.1 \text{ ksi}$   
 which is the same as  $S_{12S}$  as expected.

Example 4.2. Calculate the transverse interlaminar shear strength ( $S_{23S}$ ) for an AS/E (IMHS) with 0.6 fiber volume ratio. Using  $S_{mS}$  from example 4.1, figure 6, and respective properties from table 1 and 2 in the second equation (1), figure 6:

$$S_{23S} = \left[ \frac{1.0 - \sqrt{0.6}(1.0 - 0.185/1.0)}{1.0 - 0.6(1.0 - 0.185/1.0)} \right] \times 9.7 = 7.0 \text{ ksi}$$

Note that  $S_{23S} = 0.85 S_{13S}$  indicating that the ply is weaker in transverse interlaminar shear than in longitudinal interlaminar shear strength.

Example 4.3. Calculate (1) the longitudinal short-beam-shear ( $S_{L13SB}$ ) for the composite in example 4.1; and (2) the transverse short-beam-shear ( $S_{L23SB}$ ) in example 4.2.

1. Using  $S_{L13S} = 8.1$  in the first of equation (2), figure 6  
 $S_{L13SB} = 1.5 \times 8.1 = 12.1 \text{ ksi}$   
 This value is in reasonably good agreement, under estimating by 14 percent, with the typical measured value of 14 ksi in table 3.
2. Using  $S_{L23S} = 7.0$  in the second of equation (2), figure 6  
 $S_{L23SB} = 1.5 \times 7.0 = 10.5 \text{ ksi}$   
 Measured values for this strength are not available for comparison.

Example 4.4. Calculate the ply longitudinal flexural strength ( $S_{L11F}$ ) for an AS/E (IMHS) composite with 0.6 fiber volume ratio. Using  $k_f = 0.6$ ,  $S_{fC} = 0.9 S_{fT}$ , and  $S_{fT} = 350 \text{ ksi}$  (table 1) in the first of equation (3), figure 6.

$$S_{L11F} = \frac{3 (0.6) (350)}{1.0 + 1.0/0.9} = 298 \text{ ksi}$$

This value over estimates the typical measured data of 230 ksi by about 30 percent. A lower estimate for this strength is obtained by using  $S_{L11T} = 210 \text{ ksi}$  (from example 3.1) and  $S_{L11C} = 118 \text{ ksi}$  (from example 3.2) in the following equation:

$$S_{L11F} = \frac{3 S_{L11T}}{1 + S_{L11T}/S_{L11C}} = \frac{3 \times 210}{1.0 + 210/118} = 227 \text{ ksi}$$

which estimates the measure value of 230 ksi almost exactly. This is definitely a very good estimate considering the simplicity of the equations and the uncertainties associated with longitudinal compression failure (ref. 6). It also illustrates, in part, that flexural failure is probably a complex combination of tension, compression, and intralaminar shear failures.

Example 4.5. Calculate the ply transverse flexural strength of an AS/E (IMHS) composite with 0.6 fiber volume ratio. Using  $k_f = 0.6$  and respective property values from tables 1 and 2 in the second of equation 3.

$$S_{L22F} = \left\{ \frac{3 [1.0 - (\sqrt{0.6} - 0.6) (1.0 - 0.5/2.0)]}{1.0 + 15/35} \right\} 15 = 27.4 \text{ ksi}$$

This over estimates the typical value of 18 ksi (table 3) by about 52 percent. As was the case for longitudinal flexural strength, a lower estimate can be obtained by substituting  $S_{L22T} = 7.8 \text{ ksi}$  (from example 3.3 with partial interfacial bond) and  $S_{L22C} = 30.4 \text{ ksi}$  (example 3.4) in the following equation

$$S_{L22F} = \frac{3 \times S_{L22T}}{1 + S_{L22T}/S_{L22C}} = \frac{3 \times 7.8}{1.0 + 7.8/30.4} = 18.6 \text{ ksi}$$

which is almost equal to the typical measured values of 18 ksi (table 3).

Example 4.6. Calculate the effect of 3 percent voids on the longitudinal flexural strength for an AS/E (IMHS) with 0.6 fiber volume ratio. The first of equation (3) shows no void effect. However, the lower estimate equation in example (4.4) indicated that the compression strength predicted by the second of equation (3) should be used. This is calculated using the following steps:

1.  $S_{mS}$  degraded for voids (eq. (4), fig. 6)  
 $S_{mS} = \{1.0 - [4 (0.03)/(1.0 - 0.6) \pi]^{1/2}\} \times 13 = 9.0 \text{ ksi}$
2. Intralaminar shear strength  $S_{l12S}$  (eq. (5), fig. 5) with  $S_{mS}$  from step 1.  
 $S_{l12S} = [1 - (0.6 - 0.6)(1.0 - 0.185/2.0)] 9.0 = 7.6 \text{ ksi}$
3.  $S_{mT}$  degraded for voids, void degradation ratio same as in step 1 for  $S_{mS}$   
 $S_{mT} = \{1.0 - [4 (0.03)/(1.0 - 0.6) \pi]^{1/2}\} \times 15 = 10.4 \text{ ksi}$
4. Longitudinal compression  $S_{l11C}$  (second of eq. (2), fig. 5)  
 $S_{l11C} = 10.0 \times 7.6 + 1.5 \times 10.4 = 102 \text{ ksi}$
5. Longitudinal flexural strength (lower estimate equation, example 4.4)  
 $S_{l11F} = 3 \times 210/(1.0 + 210/102) = 206 \text{ ksi}$

which is about 9 percent less than the 227 ksi value calculated without voids in example 4.4. Two points are worth noting: (1) step (4) results in a void degradation of about 13 percent in  $S_{l11C}$  and (2) the void degradation is more severe for the longitudinal compression strength than for the longitudinal flexural strength (13 percent versus 9 percent respectively).

The above calculations show that the composite micromechanics equations in figure 6 and the alternates in Examples 4.4 and 4.5 can be used to obtain reasonable estimates for through-the-thickness uniaxial strengths. The calculations also show that the equations can be used to interpret measured data. In either case, these equations should be used judiciously.

#### UNIAXIAL FRACTURE "TOUGHNESS"

Fracture toughness is a measure of a material to resist defects such as holes, slits and notches. Fracture toughness is described by fracture toughness parameters associated with distinct fracture modes (ref. 7). Three fracture modes are generally considered: opening mode (Mode I), in-plane shear (Mode II) and out-of-plane shear (Mode III). In the case of unidirectional composites and assuming full thickness penetration defects, there are three major in-plane fracture toughness parameters herein defined as: (1) longitudinal fracture toughness ( $S_{l11T}$ ); (2) transverse fracture toughness ( $S_{l22T}$ ); and (3) in-plane (intralaminar) shear fracture toughness ( $S_{l12S}$ ). These three are parallel to the uniaxial in-plane strengths  $S_{l11T}$ ,  $S_{l22T}$  and  $S_{l12S}$ , respectively. These fracture toughness parameters are used herein to denote far-field stress required to produce additional damage in the composite. It is not clear whether far field shear stress will produce Mode II fracture in unidirectional composites or some component of Mode I (opening) fracture. In view of this we consider only Mode I, opening fracture modes  $S_{l11T}$  and  $S_{l22T}$ .

The equations describing the longitudinal and transverse fracture toughness parameters ( $S_{l11T}$  and  $S_{l22T}$ ) are given in figure 7 (ref. 8) with attendant schematics. Two sets of equations are given. In the first set (eq. (1) and (2)),  $S_{l11T}$  and  $S_{l22T}$  are expressed in terms of ply properties while in the second set (eq. (3) and (4)) they are expressed in terms of constituent properties. It can be seen in Eqs. (3) and (4) that: (1)  $S_{l11T}$  depends linearly on  $S_{fT}$  and depends in a complex way on  $K_f$ ,  $(E_{f11}/E_m)$ ,  $(E_m/E_{f22})$ ,  $(G_m/G_{f12})$  and  $\nu_m$ ; and (2)  $S_{l22T}$  depends linearly on  $S_{mT}$  and in a complex way on the other constituent material properties. Examining only key parameters  $k_f$ ,  $E_{f11}$ ,  $E_m$ ,  $S_{fT}$  and  $S_{mT}$ ,  $S_{l11T}$  increases with increasing  $k_f$ ,  $E_{f11}$ ,  $E_m$  and with decreasing  $E_{f11}$ ,

while  $\mathcal{L}_{22T}$  increases with increasing  $E_{f11}$ ,  $S_{mT}$  and with decreasing  $k_f$  and  $E_m$ . Equations (3) and (4), figure 7, are cumbersome to use. It is easier to use equation (1) and (2), figure 7, in conjunction with the ply mechanical properties equations summarized in figure 8. Two examples below illustrate use of these equations and interpretation of the results.

Example 5.1. Calculate the longitudinal fracture toughness of an AS/E (IMHS) composite with 0.6 fiber volume ratio. This is accomplished using the following steps together with equations from figures 7 and 8, and respective constituent properties from tables 1 and 2.

1. Calculate  $S_{211T}$  (eq. (1), fig. 5)  
 $S_{211T} = 0.6 \times 350 = 210 \text{ ksi}$
2. Calculate  $E_{211}$  (first equation, fig. 8)  
 $E_{211} = 0.6 \times 31 + 0.4 \times 0.5 = 18.8 \text{ mpsi}$
3. Calculate  $E_{222}$  (second equation, fig. 8)  
 $E_{222} = 0.5 / [1.0 - \sqrt{0.6(1.0 - 0.5/2.0)}] = 1.2 \text{ mpsi}$
4. Calculate  $v_{12}$  (fifth equation, fig. 8)  
 $v_{12} = 0.6 \times 0.20 + 0.4 \times 0.35 = 0.26$
5. Calculate  $G_{212}$  (third equation, fig. 8)  
 $G_{212} = 0.185 / [1.0 - \sqrt{0.6(1 - 0.185/2.0)}] = 0.62 \text{ mpsi}$
6. Calculate  $\mathcal{L}_{211T}$  (eq. (1), fig. 7)  
 $\mathcal{L}_{211T} = 210 / \{1.0 + [2 (18.8/1.2 - 0.26) + (18.8/0.62)]^{1/2}\} = 24 \text{ ksi}$

This implies that the far-field (P/A-type) ply stress will be 24 ksi when the crack-like defect starts growing. This can also be interpreted as follows: The stress required to produce additional damage is reduced by a factor of about ten compared to that in a ply without defects.

Example 5.2. Calculate the transverse fracture toughness ( $\mathcal{L}_{222T}$ ) in an AS/E (IMHS) composite with 0.6 fiber volume ratio. This is calculated using appropriate equations figures 7 and 8, respective properties from Tables 1 and 2 and the following steps.

1. Calculate  $E_{211}$ . From example 5.1 step 2,  $E_{211} = 18.8 \text{ mpsi}$
2. Calculate  $S_{222T}$  (eq. (3), fig. 5) with partial interfacial bond.
  - a.  $S_{mT} = \{1.0 - [4 (0.05)/(1.0 - 0.6) \pi]^{1/2}\} 15 = 9.0 \text{ ksi}$
  - b.  $S_{211T} = [1.0 - (\sqrt{0.6} - 0.6) (1.0 - 0.5/2.0)] \times 9.0 = 7.8 \text{ ksi}$
3. Calculate  $E_{222}$ . From example 5.1, step 3,  $E_{222} = 1.2 \text{ mpsi}$
4. Calculate  $v_{12}$ . From example 5.1, step 4,  $v_{12} = 0.26$
5. Calculate  $G_{212}$ . From example 5.1, step 5,  $G_{212} = 0.62 \text{ mpsi}$
6. Calculate  $\mathcal{L}_{222T}$ . From equation (2), figure 7

$$\mathcal{L}_{222T} = 7.8 / \{1.0 + (1.2/18.8)^{1/2} [2 (1.0 - 0.26) + 18.8/0.62]^{1/2}\} = 3.2 \text{ ksi}$$

This implies that the far-field (P/A-type) ply stress will be 3.2 ksi when additional damage in the vicinity of the defect will occur. Or alternatively, the stress required to produce additional damage is reduced by a factor of about 2.5 compared to that in a ply without defects. It is worth noting that this relatively low value of 3.2 ksi required to produce additional damage is a major contributor to the brittle-like strength behavior transverse to the fiber direction.

## UNIAXIAL IMPACT RESISTANCE--IN-PLANE

Uniaxial impact resistance of unidirectional composites is defined herein as an in-plane uniaxial impact energy density. It is denoted by the generic symbol  $X_u$  and is associated with a corresponding in-plane uniaxial impact stress. There are five impact energy densities: (1) longitudinal tension ( $X_{111T}$ ); (2) longitudinal compression ( $X_{111C}$ ); (3) transverse tension ( $X_{222T}$ ); (4) transverse compression ( $X_{222C}$ ) and intralaminar shear ( $X_{12S}$ ). The composite micromechanics equations for these impact energy densities are summarized in figure 9 with attendant schematics. The wiggly arrows in the schematics denote dynamic stresses. These equations are derived by assuming linear stress-strain behavior to fracture (fig. 3) under dynamic stress. The first five equations describe the five in-plane uniaxial impact energy densities while the last equation describe the void degradation effect as mentioned previously.

The following are observed from the equations in figure 9: (1)  $X_{111T}$  varies linearly with  $k_f$ , quadratically with  $S_{fC}$  and inversely with  $E_{f11}$ ; (2)  $X_{111C}$  also varies linearly with  $k_f$ , quadratically with  $S_{fC}$  (assuming fiber compressive fracture) and inversely with  $E_{f11}$ ; (3)  $X_{222T}$  decreases nonlinearly with  $k_f$ , increases quadratically with  $S_{mT}$ , decreases inversely with  $E_m$ , and increases nonlinearly with increasing ratio ( $E_m/E_{f22}$ ); (4)  $X_{222C}$ , and  $X_{12S}$  are matrix dominated; and (6) the matrix dominated impact energy densities decrease nonlinearly with increasing void content. Several examples below illustrate use of the equations in figure 9.

Example 6.1. Calculate the longitudinal tensile impact energy density for an AS/E (IMHS) unidirectional composite with 0.6 fiber volume ratio. Using respective properties from table 1 and  $k_f = 0.6$  in equation 1, figure 9.

$$X_{111T} = 0.6 \times 350\,000^2 / 2 \times 31\,000\,000 = 1185 \text{ (lb/sq in.) / cu in.}$$

Example 6.2. Calculate the longitudinal compressive impact energy density for an AS/E (IMHS) unidirectional composite with 0.6 fiber volume ratio. Using  $S_{fC} = 0.9S_{fT}$ ,  $S_{fT} = 350$  ksi,  $E_{f11} = 31$  mpsi and  $k_f = 0.6$  in equation 2, figure 9.

$$X_{111C} = 0.6 \times (0.9 \times 350\,000)^2 / 2 \times 31\,000\,000 = 960 \text{ (lb/sq in.) / cu in.}$$

It is instructive to calculate  $X_{111C}$  assuming delamination/shear fracture mode (example 3.2). For this case  $X_{11C} = 370$  (lb/sq in.) / cu in. or a decrease of about 61 percent.

Example 6.3. Calculate the transverse tensile impact energy density ( $X_{222T}$ ) for an AS/E (IMHS) unidirectional composite with 0.6 fiber volume ratio. Using respective property values from tables 1 and 2 and  $k_f = 0.6$  in equation 3, figure 9 and degrading  $S_{mT}$  for incomplete interfacial bond (example 3.3)

$$\begin{aligned} S_{mT} &= \{1.0 - (4(0.05)/(1.0 - 0.6)\pi)^{1/2}\} 15 = 9 \text{ ksi} \\ X_{222T} &= [1.0 - (\sqrt{0.6} - 0.6)(1.0 - 0.5/2.0)]^2 \\ &\quad \times [1.0 - \sqrt{0.6}(1.0 - 0.5/2.0)] \times 9000^2 / 2 \times 500\,000 \\ &= 26 \text{ (lb/sq in.) / cu in.} \end{aligned}$$

This value is about 2 percent of the longitudinal tensile (1185 (lb/sq in.) / cu in., example 6.1) and illustrates the fragile nature of unidirectional composites when subjected to transverse loads.



Example 6.4. Calculate the transverse compressive impact energy density for an AS/E (IMHS) unidirectional composite with 0.6 fiber volume ratio. Recall that incomplete bond does not degrade the transverse compressive behavior (example 3.4). Using respective property values from tables 1 and 2 and  $k_f = 0.6$  in equation (4), figure 9

$$\begin{aligned} \mathcal{E}_{222c} &= [1.0 - (\sqrt{0.6} - 0.6) (1.0 - 0.5/2.0)]^2 \\ &\quad \times [1.0 - 0.6(1 - 0.5/2.0)] \times 35\,000^2/2 \times 500\,000 \\ &= 388 \text{ (lb/sq in.)/cu in.} \end{aligned}$$

which is about 15 times  $\mathcal{E}_{222T}$  indicating substantial "tougher" behavior in transverse compression. Also  $\mathcal{E}_{222c}$  is about the same as that for  $\mathcal{E}_{111c}$  (370 (lb/sq in.)/cu. in.) calculated by assuming delamination/shear compression fracture mode (example 6.2). This implies that longitudinal compression and transverse compression fractures probably occur simultaneously during normal impact.

Example 6.5. Calculate the intralaminar shear energy density for an AS/E (IMHS) unidirectional composite with 0.6 fiber volume ratio. Using respective property values from tables 1 and 2 and  $k_f = 0.6$  in equation (5), figure 9 and degrading  $S_{ms}$  for incomplete interfacial bond (example 3.4)

$$\begin{aligned} \mathcal{E}_{12S} &= [1.0 - (\sqrt{0.6} - 0.6) (1.0 - 0.185/2.0)]^2 \\ &\quad \times [1.0 - \sqrt{0.6} (1.0 - 0.185/2.0)] \times 9700^2/2 \times 185\,000 \\ S_{ms} &= \left\{ 1.0 - [4 (0.02)/(1.0 - 0.6) \pi]^{1/2} \right\} \times 13 = 9.7 \text{ ksi} \end{aligned}$$

The effects of voids on matrix dominated impact energy densities can be calculated by degrading the matrix strength first using equation 6, figure 9 and then substituting the degraded value in the appropriate equation. See also example 3.6.

#### UNIAXIAL IMPACT RESISTANCE--THROUGH-THE-THICKNESS

Through-the-thickness impact resistance in unidirectional composites result from out-of-plane normal impacts. These are defined herein as impact energy densities, are denoted by the generic symbol  $\mathcal{E}_i$  and are, respectively: (1) longitudinal interlaminar shear ( $\mathcal{E}_{13S}$ ); (2) transverse interlaminar shear ( $\mathcal{E}_{23S}$ ); (3) longitudinal flexure ( $\mathcal{E}_{11F}$ ) and transverse flexure ( $\mathcal{E}_{22F}$ ). Each of these impact energy densities is associated with a dynamic stress corresponding, respectively to:  $S_{13S}$ ,  $S_{23S}$ ,  $S_{11F}$  and  $S_{22F}$ . There is also a through-the-thickness normal impact energy density. However, this impact energy density is the same as the in-plane impact energy density  $\mathcal{E}_{22T}$  or  $\mathcal{E}_{22c}$  described in section 6.

The composite micromechanics equations for through-the-thickness impact energy densities are summarized in figure 10 with attendant schematics. The following are observed from the equations in figure 10: (1)  $\mathcal{E}_{13S}$  is the same as  $\mathcal{E}_{12S}$ ; it decreases nonlinearly with increasing  $k_f$ , increases nonlinearly with increasing ratio ( $G_m/G_{f12}$ ), it increases quadratically with  $S_{ms}$  and increases inversely as  $G_m$  decreases; (2)  $\mathcal{E}_{23S}$  has about the same behavior as  $\mathcal{E}_{13S}$ ; (3)  $\mathcal{E}_{11F}$  increase linearly with  $k_f$  and quadratically with  $S_{fT}$ , and increases inversely as  $E_{f11}$  and the ratio ( $S_{fT}/S_{fc}$ ) decrease; (4)  $\mathcal{E}_{22F}$  decreases nonlinearly with increasing  $k_f$  and with increasing ratio  $E_m/E_{f22}$ , increases quadratically with  $S_{mT}$ , increases inversely as the square of the



( $S_{mT}/S_{mc}$ ) ratio and increases as  $E_m$  decreases. Several examples below illustrate use of the equations in figure 10.

Example 7.1. Calculate the longitudinal interlaminar shear impact energy density ( $X_{l13S}$ ) for an AS/E (IMHS) unidirectional composite with 0.6 fiber volume ratio. Since  $X_{l13S}$  is the same as  $X_{l12S}$ , (the equation for  $X_{l13S}$  is identical to eq. 5, fig. 9) from example 6.5.  
 $X_{l13S} = X_{l12S} = 53.5 \text{ (lb/sq.in./cu.in.)}$

Example 7.2. Calculate the transverse interlaminar shear impact energy density ( $X_{l23S}$ ) for an AS/E (IMHS) unidirectional composite with 0.6 fiber volume ratio. Using respective property values from tables 1 and 2, and  $k_f = 0.6$  in equation for  $X_{l23S}$ , figure 10, and degrading  $S_{mS}$  for incomplete interfacial bond.

$$S_{mS} = \{[1.0 - [4(0.02)/(1.0 - 0.6)\pi]^{1/2}\} 13 = 9.7 \text{ ksi}$$

$$X_{l23S} = [1.0 - 0.6(1.0 - 0.185/1.0)]^2 \frac{9700^2}{2} \times 185\,000 [1 - 0.6(1.0 - 0.185/1.0)] = 67.7 \text{ (lb/sq in.)/cu in.}$$

It is interesting to note that for this example  $X_{l23S}$  is about 22 percent greater than  $X_{l13S}$ . This increase is mainly due to  $G_{f23}$  which is about 50 percent of  $G_{f12}$ . Based on the relative values for  $X_{l13S}$  and  $X_{l23S}$  interlaminar damage will occur first due to dynamic  $\sigma_{l23}$ .

Example 7.3. Calculate the longitudinal flexural impact energy density ( $X_{l11F}$ ) for an AS/E (IMHS) unidirectional composite with 0.6 fiber volume ratio. Using respective property values from tables 1 and 2 and  $k_f = 0.6$  in the equation for  $X_{l11F}$ , figure 10 (assuming  $S_{fc} = 0.9 S_{fT}$ ):

$$X_{l11F} = 4.5 \times 0.6 \times 350\,000^2 / 31\,000\,000 \times (1.0 + 1.0/0.9)^2 = 2394 \text{ (lb/sq in.) cu in.}$$

An alternate estimate is to use  $S_{l11T} = 210 \text{ ksi}$  from example 3.1,  $S_{l11C} = 118 \text{ ksi}$  from example 3.2 and  $E_{l11} = 18.8 \text{ mpsi}$  from example 5.1 in the following equation

$$X_{l11F} = 4.5 \frac{S_{l11T}^2}{E_{l11}} (1.0 + S_{l11T}/S_{l11C})^2$$

$$X_{l11F} = 4.5 \times 210\,000^2 / 18\,800\,000 \times (1.0 + 210/118)^2 = 1366 \text{ (lb/sq. in.) cu. in.}$$

It is worth noting that the first estimate corresponds to  $S_{l11F} = 298 \text{ ksi}$  for fiber compression fracture; the second estimate corresponds to  $S_{l11F} = 227 \text{ ksi}$  for delamination/shear compression fracture (example 4.4). Also the second estimate is about 57 percent smaller than the first indicating that delamination/shear is a much more severe fracture mode under impact.

Example 7.4. Calculate the transverse flexural impact energy density ( $X_{l22F}$ ) for an AS/E (IMHS) unidirectional composite with 0.6 fiber volume ratio. Using respective property values from tables 1 and 2, degraded  $S_{mT}$  for incomplete interfacial bond (eq. (6), fig. 9, with  $k_v = 0.05$ ) and  $k_f = 0.6$  in the equation for  $X_{l22F}$ , figure 10.

$$S_{mT} = \{1.0 - [4(0.05)/(1.0 - 0.6)\pi]^{1/2}\} 15 = 9.0 \text{ ksi}$$

$$X_{l22F} = 4.5 [1.0 - 0.6(1.0 - 0.5/2.0)] \times \left[ \frac{1.0 - (\sqrt{0.6} - 0.6)(1.0 - 0.5/2.0)}{1 + 9/35} \right]^2 \times (9000^2 / 500\,000) = 146 \text{ (lb/sq in.)/cu in.}$$

It is worth noting that this value corresponds to  $S_{L22F} = 18.6$  ksi which is the lower estimate in example 4.5. Also  $S_{L22F}$  is about 10 percent of  $S_{L11F}$ , the lower estimate in example 7.3

The effect of voids on any of the through-the-thickness impact energy densities is determined by degrading  $S_{mT}$  or  $S_{mS}$  first using equation 6, figure 9 and then substituting this degraded  $S_m$  value in the applicable equation, figure 10. The remaining steps are identical to Examples 7.1 to 7.4.

## ENVIRONMENTAL EFFECTS

Environmental effects refer to the effects caused by the presence of moisture and temperature in composites. The combined effects are usually called hygrothermal effects. Hygrothermal effects influence all resin-dominated properties; uniaxial strengths, fracture toughness and impact resistance. Hygrothermal effects are estimated using an empirical expression (ref. 9). The empirical expression and the rotation used are summarized in figure 11. Its application to uniaxial composite strengths and strength related properties is illustrated using the following examples.

Example 8.1. Calculate the hygrothermal effects on the ply transverse strength assuming AS/E (IMHS) unidirectional composite,  $k_f = 0.6$ ,  $T = 270^\circ$  F,  $T_g = 420^\circ$  F and 1 percent moisture by weight. Several steps are required for this calculation:

1.  $T_{gd} = 420^\circ$  F table 2
2.  $T_{gw} = [0.005 (1)^2 - 0.1 (1) + 1.0] 420 = 380^\circ$  F
3. Hygrothermal degradation ratio ( $P_{HTM}/P_0$ ) for resin-dominated properties is  

$$P_{HTM}/P_0 = [(380-270)/(420-70)]^{1/2} = 0.56$$

This means that all resin dependent properties  $E_m$ ,  $G_m$  and  $S_m$  must be reduced by this ratio prior to their use in the applicable equation.

4. The reduced matrix properties (table 2) are  
 $S_{mT} = 0.56 \times 15 = 8.4$  ksi  
 $E_m = 0.56 \times 0.5 = 0.28$  mpsi
5. Degrade  $S_{mT}$  for partial interfacial bond assuming 5 percent voids by volume  

$$S_{mT} = \{1.0 - [4 \cdot (0.05)/(1 - 0.6)]^{1/2}\} 8.4 = 5.0$$
 ksi
6. Using equation 3, figure 5 with the respective degraded properties  

$$S_{L22T} = [1.0 - (\sqrt{0.6 - 0.6}) (1.0 - 0.25/2.0)] 5.0 = 4.2$$
 ksi

which is a decrease of 46 percent compared to room temperature dry 7.8 ksi (example 3.3). Obviously, this is severe degradation of the hygrothermal environment assumed in the example. It is important to note that the ratio of environmentally degraded to room-temperature dry  $(4.2/7.8) = 0.53$  which is very close to 0.56 predicted in step 3 above. This indicates that the hygrothermal degradation ratio can be applied to either (1) resin or (2) resin-dominated composite properties equally well (ref. 9). It is recommended to use the glass transition temperature of the composite for the second case. The glass transition temperature of the composite is about  $50^\circ$  F greater than that of the resin.

Example 8.2. Calculate the transverse flexural strength for the same composite and environmental conditions as in example 8.1. Again several steps are required

1. From example 8.1, step 3  
 $P_{HTM}/P_0 = 0.56$   
 from which follows:  $S_{mC} = 0.56 \times 35 = 19.6 \text{ ksi}$  and  $E_m = 0.28 \text{ mpsi}$
2. The transverse compression stress is  
 $S_{L22C} = [1.0 - (\sqrt{0.6} - 0.6) (1.0 - 0.28/2.0)] 19.6 = 16.7 \text{ ksi}$
3. Using  $S_{L22C} = 16.7 \text{ ksi}$  and  $S_{L22T} = 4.2 \text{ ksi}$  (example 8.1, step 6) in the lower estimate equation (example 4.5).  
 $S_{L22F} = 3 \times 4.2 / (1.0 + 4.2/16.7) = 10.1 \text{ ksi}$

which is about 0.54 of 18.6 ksi, the room temperature dry value calculated in example 4.5. This calculation also illustrates that the hygrothermal degradation can be applied to a resin-dominated composite property.

Example 8.3. Calculate the transverse fracture toughness ( $\mathcal{K}_{L22T}$ ) for the composite and hygrothermal environment in example 8.1. The procedure for this calculation is the same as that in example 5.2.

1. Using the  $(P_{HTM}/P_0) = 0.56$  in the equations for  $E_{L22}$  and  $G_{L12}$ , figure 8.  
 $E_{L22} = 0.28 / [1.0 - \sqrt{0.6} (1.0 - 0.28/2.0)] = 0.839 \text{ mpsi}$   
 $G_{L12} = 0.103 / [1.0 - \sqrt{0.6} (1.0 - 0.103/2.0)] = 0.39 \text{ mpsi}$
2.  $E_{L11}$  and  $\nu_{L12}$  remain practically unchanged.  
 $E_{L11} = 18.7$  and  $\nu_{L12} = 0.26$  (example 5.1, steps 2 and 4)
3.  $S_{L22T} = 4.2 \text{ ksi}$  (example 8.1, step 6)
4. Substituting respective values from steps 1, 2, and 3 in equation 2, figure 7

$$\mathcal{K}_{L22T} = 4.2/1.0 + (0.84/18.7)^{1/2} \times [2 (1.0 - 0.26) + 18.7/0.39]^{1/2} = 1.7 \text{ ksi}$$

which is about 0.53 of the value calculated in example 5.2. Even in this complex expression the environment degrades the composite-resin dominated property in about the same ratio as the resin property.

Example 8.4. Calculate the transverse impact energy density ( $\mathcal{E}_{L22T}$ ) for the composite and environmental conditions in example 8.1. The procedure for this calculation is the same as that in example 6.3.

1. The degraded properties needed for equation 3, figure 9 are  
 $E_m = 0.28 \text{ mpsi}$  (example 8.1, step 4 and  $S_{mT} = 5.0 \text{ ksi}$  (example 8.1, step 5).
2. Using respective values in equation 3, figure 9  
 $\mathcal{E}_{L22T} = [1.0 - (\sqrt{0.6} - 0.6) (1.0 - 0.28/2.0)]^2$   
 $\times [1.0 - \sqrt{0.6} (1.0 - 0.28/2.0)] \times 5000^2/2 \times 280 \text{ 000}$   
 $= 10.8 \text{ (lb/sq. in.) cu. in.}$

which is about 42 percent of 26 (lb/sq in.)/cu in., in the room temperature dry value in example 6.3. This ratio corresponds to a decrease of about equal to the hygrothermal degradation ratio raised to the 3/2 power or  $(0.56)^{3/2}$ . Indicating again that resin dominated composite properties

degrade in the same ratio as the resin when subjected to hygrothermal environments.

## GENERAL DISCUSSION

The several examples presented illustrate the usefulness and advantage of having a unified set of micromechanics equations summarized in Figs. 5 to 11 for the strength, fracture toughness and impact resistance of composites. The examples also illustrate how the various strengths and other mechanical properties are interrelated. In addition, they provide detailed and quantitative insight into the micromechanic strength behavior of composites. Furthermore, the various equations can be selectively used to conduct parametric studies as well as sensitivity analyses to assess acceptable ranges of various constituent material and environmental factors.

Limited comparisons were provided between predicted values and available measured data for some of the numerical examples. It is important to note that the primary purpose of this report is to describe a unified set of simple, working equations and illustrate its versatility with a variety of numerical examples. These examples demonstrate computational effectiveness and illustrate interrelationships of various strengths and other properties at the micromechanistic level. It is highly recommended that the reader use this unified set of micromechanics equations to predict various properties of interest to him and compare them with measured data or with known values. This provides a direct approach to assess the application and limitations of these equations as well as guidelines on how to modify them.

Another important aspect of having this unified set of micromechanics strength equations is that they can be used to plan and guide experimental programs for maximum benefit with minimum testing. These micromechanics equations can be advantageous in a number of other ways. Many of these other ways become "self evident" after some familiarity has been obtained.

The two tables summarizing constituent material properties illustrate the amount of data needed for effective use of a unified set of micromechanics equations. The data in these tables were compiled from many sources and many values are estimates which were inferred from predicted results and curve fits. The data are included for three main reasons: (1) to illustrate that the micromechanics equations need numerous properties; (2) to bring attention to the fact that many of these properties have not been measured and, hopefully, to stimulate enough interest to develop experimental methods to measure them; and (3) to provide indicative ranges of properties of both fibers and matrices. It cannot be overemphasized that the data should be considered dynamic in the sense that they should be continuously modified if better values are known or become available.

Lastly, the unified set of micromechanics equations described herein, in conjunction with classical laminate theories and combined stress failure criteria can be used to calculate laminate strength based on first ply failure.

## CONCLUSIONS

A unified set of composite micromechanics equations of simple form is summarized and described. This unified set includes composite micromechanics equations for predicting (1) ply in-plane uniaxial strength; (2) through-the-thickness strength (interlaminar and flexural); (3) in-plane fracture toughness; (4) in-plane impact resistance; and (5) through-the-thickness (interlaminar and flexural) impact resistance. Equations are also included for predicting the hygrothermal effects on strength, fracture toughness and impact resistance. Several numerical examples are worked out to illustrate the ease of use of the various composite micromechanics equations. The numerical examples were selected, in part, to demonstrate the interrelationship of the various constituent properties in composite strength and strength related behavior, and also to provide comparisons with available experimental data. This unified set of micromechanics equations makes it possible and cost-effective to assess composite strength, "fracture toughness", impact resistance and attendant environmental effects for preliminary designs of composite structures.

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TABLE I. - FIBER PROPERTIES<sup>a</sup>

| Name                    | Symbol           | Units                          | Boron  | HMS    | AS     | T300   | KEV     | S-G     | E-G     |
|-------------------------|------------------|--------------------------------|--------|--------|--------|--------|---------|---------|---------|
| Number of fibers/end    | N <sub>f</sub>   | -----                          | 1      | 10 000 | 10 000 | 3000   | 580     | 204     | 204     |
| Fiber diameter          | d <sub>f</sub>   | in.                            | 0.0056 | 0.0003 | 0.0003 | 0.0003 | 0.00046 | 0.00036 | 0.00036 |
| Density                 | ρ <sub>f</sub>   | lb/in. <sup>3</sup>            | 0.095  | 0.070  | 0.063  | 0.064  | 0.053   | 0.090   | 0.090   |
| Longit. modulus         | E <sub>f11</sub> | 10 <sup>6</sup> psi            | 58     | 55.0   | 31.0   | 32.0   | 22      | 12.4    | 10.6    |
| Transv. modulus         | E <sub>f22</sub> | 10 <sup>6</sup> psi            | 58     | 0.90   | 2.0    | 2.0    | 0.6     | 12.4    | 10.6    |
| Long. shear modulus     | G <sub>f12</sub> | 10 <sup>6</sup> psi            | 24.2   | 1.1    | 2.0    | 1.3    | 0.42    | 5.17    | 4.37    |
| Transv. shear modulus   | G <sub>f23</sub> | 10 <sup>6</sup> psi            | 24.2   | 0.7    | 1.0    | 0.7    | 0.22    | 5.17    | 4.37    |
| Long. Poisson's ratio   | ν <sub>f12</sub> | -----                          | 0.20   | 0.20   | 0.20   | 0.20   | 0.35    | 0.20    | 0.22    |
| Transv. Poisson's ratio | ν <sub>f23</sub> | -----                          | 0.20   | 0.25   | 0.25   | 0.25   | 0.35    | 0.20    | 0.22    |
| Heat capacity           | C <sub>f</sub>   | btu/lb/°F                      | 0.31   | 0.20   | 0.20   | 0.22   | 0.25    | 0.17    | 0.17    |
| Long. heat cond.        | K <sub>f11</sub> | btu/hr/ft <sup>2</sup> /°F/in. | 22     | 580    | 580    | 580    | 1.7     | 21      | 7.5     |
| Transv. heat cond.      | K <sub>f22</sub> | btu/hr/ft <sup>2</sup> /°F/in. | 22     | 58     | 58     | 58     | 1.7     | 21      | 7.5     |
| Long. th. exp. coef.    | α <sub>f11</sub> | 10 <sup>-6</sup> in./in./°F    | 2.8    | -0.55  | -0.55  | 0.55   | -2.2    | 2.8     | 2.8     |
| Transv. th. exp. coef.  | α <sub>f22</sub> | 10 <sup>-6</sup> in./in./°F    | 2.8    | 5.6    | 5.6    | 30     | 2.8     | 2.8     | 2.8     |
| Long. tensile strength  | S <sub>ft</sub>  | ksi                            | 600    | 250    | 350    | 350    | 400     | 600     | 400     |
| Long. compression str.  | S <sub>fc</sub>  | ksi                            | 700    | 200    | 260    | 300    | 75      | -----   | -----   |
| Shear strength          | S <sub>fs</sub>  | ksi                            | 100    | -----  | -----  | -----  | -----   | -----   | -----   |

<sup>a</sup>Transverse, shear, and compression properties are estimates inferred from corresponding composite properties.

TABLE II. - MATRIX PROPERTIES

| Name                     | Symbol          | Units                                  | LM    | IMLS  | IMHS  | HM    | Polyimide | PMR   |
|--------------------------|-----------------|--|-------|-------|-------|-------|-----------|-------|
| Density                  | ρ <sub>m</sub>  | lb/in. <sup>3</sup>                    | 0.042 | 0.046 | 0.044 | 0.045 | 0.044     | 0.044 |
| Modulus                  | E <sub>m</sub>  | 10 <sup>6</sup> psi                    | 0.32  | 0.50  | 0.50  | 0.75  | 0.50      | 0.47  |
| Shear modulus            | G <sub>m</sub>  | 10 <sup>6</sup> psi                    | ----- | ----- | ----- | ----- | -----     | ----- |
| Poisson's ratio          | ν <sub>m</sub>  | -----                                  | 0.43  | 0.41  | 0.35  | 0.35  | 0.35      | 0.36  |
| Heat capacity            | C <sub>m</sub>  | Btu/lb/°F                              | 0.25  | 0.25  | 0.25  | 0.25  | 0.25      | 0.25  |
| Heat conductivity        | K <sub>m</sub>  | Btu/hr/ft <sup>2</sup> /°F/in.         | 1.25  | 1.25  | 1.25  | 1.25  | 1.25      | 1.25  |
| Thermal exp. coef.       | α <sub>m</sub>  | 10 <sup>-6</sup> in./in./°F            | 57    | 57    | 36    | 40    | 20        | 28    |
| Diffusivity              | D <sub>m</sub>  | 10 <sup>-10</sup> in <sup>2</sup> /sec | 0.6   | 0.6   | 0.6   | 0.6   | 0.6       | 0.6   |
| Moisture exp. coef.      | β <sub>m</sub>  | in./in./M                              | 0.33  | 0.33  | 0.33  | 0.33  | 0.33      | 0.33  |
| Tensile strength         | S <sub>mt</sub> | ksi                                    | 8     | 7     | 15    | 20    | 15        | 8     |
| Compression strength     | S <sub>mc</sub> | ksi                                    | 15    | 21    | 35    | 50    | 30        | 16    |
| Shear strength           | S <sub>ms</sub> | ksi                                    | 8     | 7     | 13    | 15    | 13        | 8     |
| Tensile fracture strain  | ε <sub>mt</sub> | in./in. (%)                            | 8.1   | 1.4   | 2.0   | 2.0   | 2.0       | 2.0   |
| Compr. fracture strain   | ε <sub>mc</sub> | in./in. (%)                            | 15    | 4.2   | 5.0   | 5.0   | 4.0       | 3.5   |
| Shear fracture strain    | ε <sub>ms</sub> | in./in. (%)                            | 10    | 3.2   | 3.5   | 4.0   | 3.5       | 5.0   |
| Air heat conductivity    | K <sub>v</sub>  | Btu/hr/ft <sup>2</sup> /°F/in.         | 0.225 | 0.225 | 0.225 | 0.225 | 0.225     | 0.225 |
| Glass trans. temp. (dry) | T <sub>GD</sub> | °F                                     | 350   | 420   | 420   | 420   | 700       | 700   |

Notes: LM - low modulus; IMLS - intermediate modulus low strength; IMHS - intermediate modulus high strength; HM - high modulus.

Thermal, hygral, compression and shear properties are estimates only; G<sub>m</sub> = E<sub>m</sub>/2 (1 + ν<sub>m</sub>).

TABLE III. - TYPICAL EXPERIMENTAL VALUES FOR UNIDIRECTIONAL  
COMPOSITE (PLY) UNIAXIAL STRENGTHS<sup>(a)</sup> (KSI)

| Fiber     | Epoxy | Fiber volume ratio | Longitudinal |          | Transverse |          | In-plane shear | Flexural |        | Inter-laminar shear |
|-----------|-------|--------------------|--------------|----------|------------|----------|----------------|----------|--------|---------------------|
|           |       |                    | tension      | compres. | tension    | compres. |                | Long.    | Trans. |                     |
| Boron     | 505   | 0.50               | 230          | 360      | 9.1        | 35.0     | 12.0           | 350      | 40     | 16.0                |
| AS        | 3501  | .60                | 210          | 170      | 7.0        | 36.0     | 9.0            | 230      | 18     | 14.0                |
| HMS       | 934   | .60                | 120          | 90       | 6.7        | 28.5     | 6.5            | 150      | (b)7   | 10.5                |
| T-300     | 5208  | .60                | 210          | 210      | 6.5        | 36.0     | 9.0            | 260      | 18     | 14.0                |
| KEVLAR-49 | ----- | .60                | 200          | 40       | 4.0        | 9.4      | 8.7            | 90       | 6      | 7.0                 |
| GLASS     |       |                    |              |          |            |          |                |          |        |                     |
| S (901-S) | 10025 | .60                | 220          | 120      | 6.7        | 25.0     | 12.0           | 320      | 21     | 14.0                |
| E         | 1002  | .60                | 160          | 90       | 4.0        | 20.0     | 12.0           | 165      | 20     | 14.0                |

(a) Data in this table was compiled from refs. 2, 3, 4, 5.

(b) Estimate.



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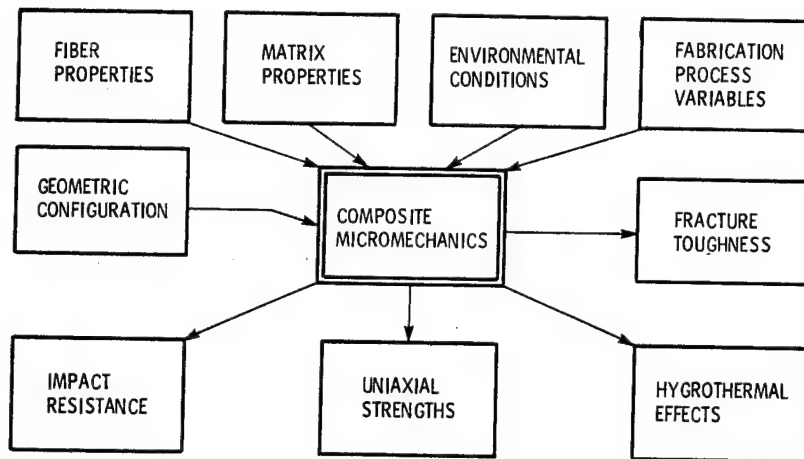


Figure 1. - Concepts, math-models and equations used to predict unidirectional composite (ply) uniaxial strengths from constituent material properties, geometric configuration, fabrication process variables and environmental conditions.

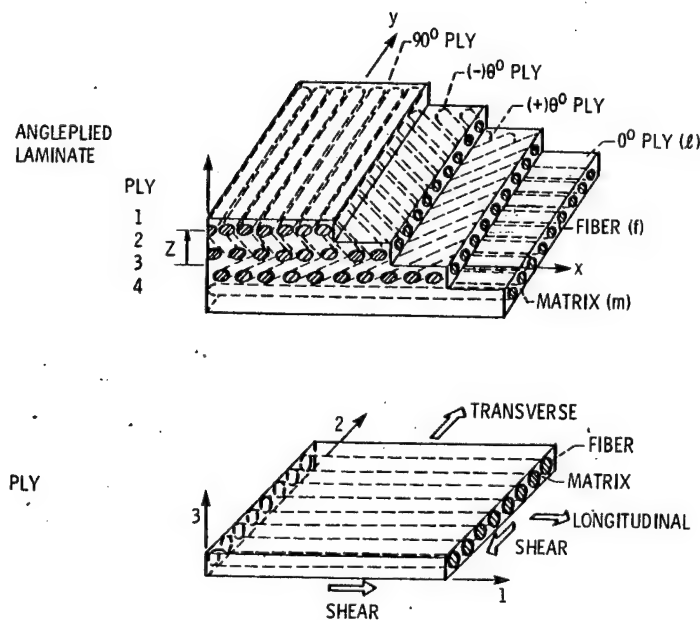


Figure 2. - Typical fiber composite geometry.

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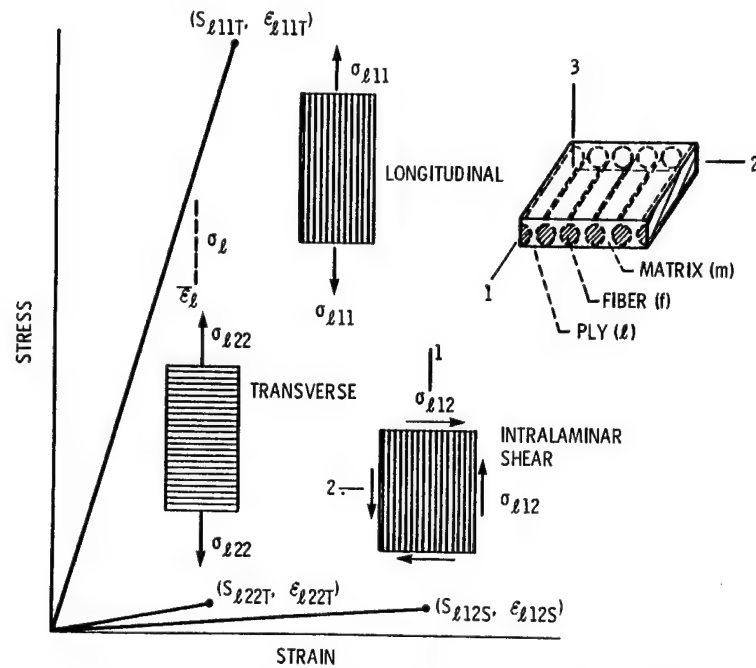


Figure 3. - Typical stress-strain behavior of unidirectional fiber composites.

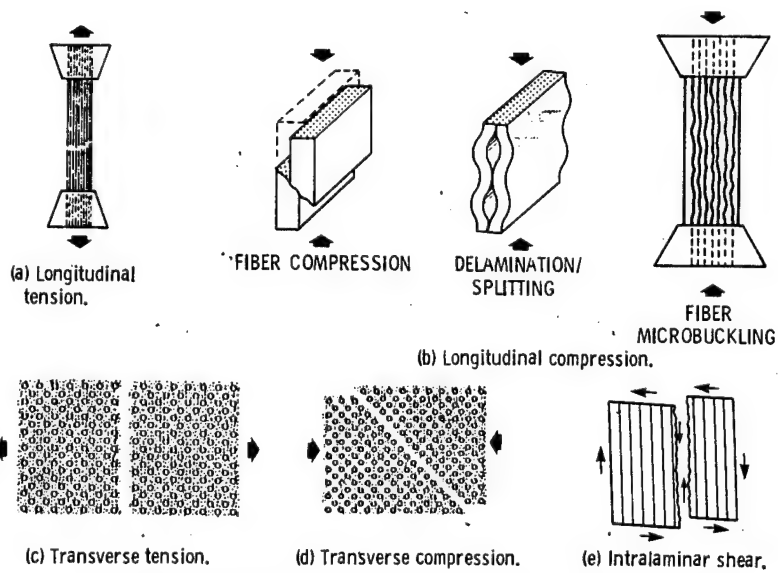


Figure 4. - In-plane fracture modes of unidirectional (ply) fiber composites.

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1. LONGITUDINAL TENSION:  $S_{L11T} \approx k_f S_{fT}$
2. LONGITUDINAL COMPRESSION:
  - FIBER COMPRESSION:  $S_{L11C} \approx k_f S_{fC}$
  - DELAMINATION/SHEAR:  $S_{L11C} \approx 10 S_{L12S} + 2.5 S_{mT}$
  - MICROBUCKLING:  $S_{L11C} \approx \frac{G_m}{1 - k_f \left( 1 - \frac{G_m}{G_{f12}} \right)}$
3. TRANSVERSE TENSION:  $S_{L22T} \approx [1 - (\sqrt{k_f} - k_f) (1 - E_m/E_{f22})] S_{mT}$
4. TRANSVERSE COMPRESSION:  $S_{L22C} \approx [1 - (\sqrt{k_f} - k_f) (1 - E_m/E_{f22})] S_{mC}$
5. INTRALAMINAR SHEAR:  $S_{L12S} \approx [1 - (\sqrt{k_f} - k_f) (1 - G_m/G_{f12})] S_{mS}$
6. FOR VOIDS:  $S_m \approx \left\{ 1 - [4k_v/(1 - k_f)\pi]^{1/2} \right\} S_m$

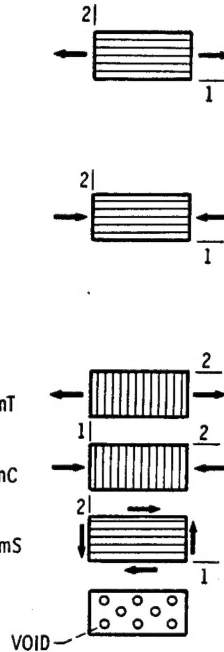


Figure 5. - Composite micromechanics: uniaxial strengths - in-plane.

1. INTERLAMINAR SHEAR:  $S_{L13S} \approx [1 - (\sqrt{k_f} - k_f) (1 - G_m/G_{f12})] S_{mS}$   
 $S_{L23S} \approx \left[ \frac{1 - \sqrt{k_f} (1 - G_m/G_{f23})}{1 - k_f (1 - G_m/G_{f23})} \right] S_{mS}$
2. SHORT BEAM SHEAR:  $S_{L13SB} \approx 1.5 S_{L13S}$   
 $S_{L23SB} \approx 1.5 S_{L23S}$
3. FLEXURAL:  $S_{L11F} \approx \frac{3 k_f S_{fT}}{1 + \frac{S_{fT}}{S_{fC}}}$   
 $S_{L22F} \approx \frac{3 [1 - (\sqrt{k_f} - k_f) (1 - E_m/E_{f22})] S_{mT}}{1 + \frac{S_{mT}}{S_{mC}}}$
4. FOR VOIDS:  $S_m \approx \left\{ 1 - [4k_v/(1 - k_f)\pi]^{1/2} \right\} S_m$

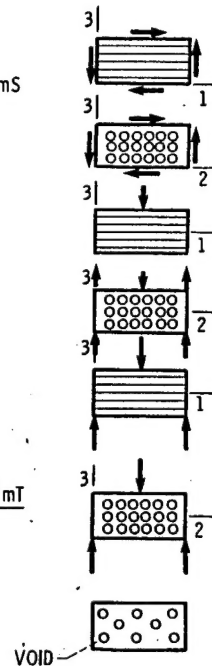
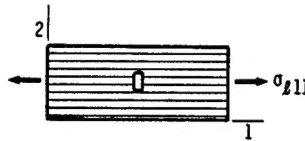


Figure 6. - Composite micromechanics: uniaxial strengths - through-the-thickness.

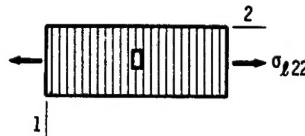
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USING PLY PROPERTIES:

$$1. \sigma_{L11T} = \frac{S_{L11T}}{1 + \left[ 2 \left( \frac{E_{L11}}{E_{L22}} - \nu_{L12} \right) + \frac{E_{L11}}{G_{L12}} \right]^{1/2}}$$



$$2. \sigma_{L22T} = \frac{S_{L22T}}{1 + \left( \frac{E_{L22}}{E_{L11}} \right)^{1/2} \left[ 2 \left( 1 - \nu_{L12} \right) + \frac{E_{L11}}{G_{L12}} \right]^{1/2}}$$



USING CONSTITUENT PROPERTIES:

$$3. \sigma_{L11T} \approx \frac{k_f S_{fT}}{1 + (2 k_f E_{f11} / E_m)^{1/2} \left\{ 2 (1 - \sqrt{k_f}) + \sqrt{k_f} \left( \frac{E_m}{E_{f22}} + \frac{G_m}{G_{f12}} \right) + \nu_m \left[ 1 - \sqrt{k_f} \left( 1 - \frac{G_m}{G_{f12}} \right) \right] \right\}^{1/2}}$$

$$4. \sigma_{L22T} = \frac{(k_f E_{f11})^{1/2} [1 - (\sqrt{k_f} - k_f) (1 - E_m / E_{f22})] [1 - \sqrt{k_f} (1 - E_m / E_{f22})]^{1/2} S_{mT}}{\left\{ k_f E_{f11} [1 - \sqrt{k_f} (1 - E_m / E_{f22})] \right\}^{1/2} + E_m \left\{ 2 [1 - k_f (\nu_{f12} + \nu_m) - \nu_m] + k_f [1 - \sqrt{k_f} (1 - G_m / G_{f12})] (E_{f11} / G_m) \right\}^{1/2}}$$

$$5. \sigma_{L22} \approx \frac{[1 - \sqrt{k_f} - k_f] (1 - E_m / E_{f22}) [1 - \sqrt{k_f} (1 - E_m / E_{f22})]^{1/2} S_{mT}}{[1 - \sqrt{k_f} (1 - E_m / E_{f22})]^{1/2} + [2 (1 + \nu_m)]^{1/2} [1 - \sqrt{k_f} (1 - G_m / G_{f12})]^{1/2}}$$

Figure 7. - Composite micromechanics: uniaxial fracture "toughness".

LONGITUDINAL MODULUS:

$$E_{L11} = k_f E_{f11} + k_m E_m$$

TRANSVERSE MODULUS:

$$E_{L22} = \frac{E_m}{1 - \sqrt{k_f} (1 - E_m / E_{f22})} = E_{L33}$$

SHEAR MODULUS:

$$G_{L12} = \frac{G_m}{1 - \sqrt{k_f} (1 - G_m / G_{f12})} = G_{L13}$$

SHEAR MODULUS:

$$G_{L23} = \frac{G_m}{1 - k_f (1 - G_m / G_{f23})}$$

POISSON'S RATIO:

$$\nu_{L12} = k_f \nu_{f12} + k_m \nu_m = \nu_{L13}$$

POISSON'S RATIO:

$$\nu_{L23} = k_f \nu_{f23} + k_m \left( 2 \nu_m - \frac{\nu_{L12}}{E_{L11}} E_{L22} \right)$$

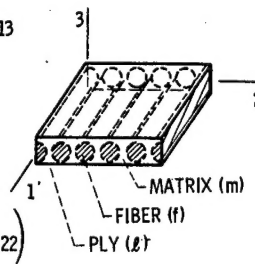


Figure 8. - Composite micromechanics, mechanical properties.

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1. LONGITUDINAL TENSION:  $\mathcal{E}_{l11T} \approx k_f S_{fT}^2 / 2E_{f11}$
2. LONGITUDINAL COMPRESSION:  $\mathcal{E}_{l11C} \approx k_f S_{fC}^2 / 2E_{f11}$
3. TRANSVERSE TENSION:  $\mathcal{E}_{l22T} \approx [1 - (\sqrt{k_f} - k_f) (1 - E_m/E_{f22})]^2 \times [1 - \sqrt{k_f} (1 - E_m/E_{f22})] S_{mT}^2 / 2E_m$
4. TRANSVERSE COMPRESSION:  $\mathcal{E}_{l22C} \approx [1 - (\sqrt{k_f} - k_f) (1 - E_m/E_{f22})]^2 \times [1 - \sqrt{k_f} (1 - E_m/E_{f22})] S_{mC}^2 / 2E_m$
5. INTRALAMINAR SHEAR:  $\mathcal{E}_{l12S} \approx [1 - (\sqrt{k_f} - k_f) (1 - G_m/G_{f12})]^2 \times [1 - \sqrt{k_f} (1 - G_m/G_{f12})] S_{mS}^2 / 2G_m$
6. FOR VOIDS:  $S_m \approx \{1 - [4 k_v / (1 - k_f) \pi]^{1/2}\} S_m$

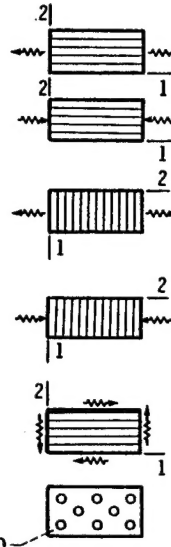


Figure 9. - Composite micromechanics: uniaxial impact resistance - in-plane. (Energy absorbed per unit volume  $\mathcal{E}_{l2}$ .)

1. INTERLAMINAR SHEAR:  $\mathcal{E}_{l13S} \approx [1 - (\sqrt{k_f} - k_f) (1 - G_m/G_{f12})]^2 \times [1 - \sqrt{k_f} (1 - G_m/G_{f12})] S_{mS}^2 / 2G_m$   
 $\mathcal{E}_{l23S} \approx \frac{[1 - \sqrt{k_f} (1 - G_m/G_{f23})]^2 S_{mS}^2}{2G_m [1 - k_f (1 - G_m/G_{f23})]}$
2. FLEXURAL:  $\mathcal{E}_{l11F} \approx \frac{4.5 k_f S_{fT}^2}{E_{f11} \left(1 + \frac{S_{fT}}{S_{fC}}\right)^2}$   
 $\mathcal{E}_{l22F} \approx 4.5 [1 - \sqrt{k_f} (1 - E_m/E_{f22})] \times \left\{ \frac{[1 - (\sqrt{k_f} - k_f) (1 - E_m/E_{f22})]^2}{(1 + S_{mT}/S_{mC})} \right\}^2 \left( \frac{S_{mT}^2}{E_m} \right)$

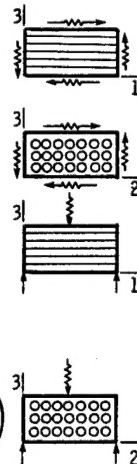


Figure 10. - Composite micromechanics: uniaxial impact resistance - through-the-thickness. (Energy absorbed per unit volume.)

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$$\left. \begin{array}{l} \text{GLASS TRANSITION} \\ \text{TEMP. OF WET RESIN} \end{array} \right\} T_{GW} = (0.005 M_m^2 - 0.10 M_m + 1.0) T_{GD}$$

$$\left. \begin{array}{l} \text{EFFECTS ON MECHANICAL} \\ \text{PROPERTIES} \end{array} \right\} \frac{P_{HTM}}{P_O} = \left[ \frac{T_{GW} - T}{T_{GW} - T_O} \right]^{1/2}$$

$$\left. \begin{array}{l} \text{EFFECTS ON THERMAL} \\ \text{PROPERTIES} \end{array} \right\} \frac{P_{HTT}}{P_O} = \left[ \frac{T_{GD} - T_O}{T_{GW} - T} \right]^{1/2}$$

$$\left. \begin{array}{l} \text{GLASS TRANSITION} \\ \text{TEMP. OF WET RESIN} \end{array} \right\} T_{GW} = T + (T_{GD} - T_O) (P_{HTM}/P_O)^2$$

TEMPERATURE (T) ANY CONSISTANT UNITS

MOISTURE (M) WEIGHT PERCENT ( $M \leq 10\%$ )

SUBSCRIPTS: G = TRANSITION; D = DRY; W = WET; O = REFERENCE

HTM = HYGROTHERMAL MECHANICAL, HTT = HYGROTHERMAL THERMAL

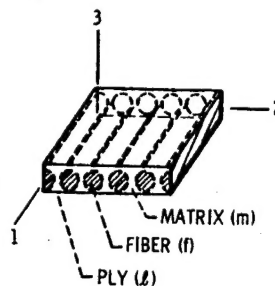


Figure 11. - Governing equations: micromechanics - hygrothermal effects.